Digital Twin of Agricultural Machinery Equipment: From Concept to Application Postprint

Authors: Guo Dafang, Du Yuefeng, Wu Xiuheng, Hou Siyu, Li Xiaoyu, Zhang Yan' an, Chen Du

Date: 2023-08-14T00:00:00+00:00

Abstract

[Objective/Significance] Agricultural machinery equipment serves as the material foundation for implementing advanced agricultural production concepts. How to improve the design and manufacturing standards as well as operation, maintenance, and control capabilities of agricultural machinery equipment, and to fully leverage equipment performance, constitutes a core challenge facing the future development of smart agriculture. Digital twin is an advanced concept that integrates multiple information technologies and promotes the fusion of virtual and real interactions, which helps to achieve a clearer understanding of agricultural machinery equipment and its operational processes, thereby addressing complex issues from the design to recycling stages, comprehensively improving operational quality of agricultural machinery equipment, and better meeting agricultural production demands. [Progress] First, focusing on the application of digital twin in the field of agricultural machinery equipment, we summarize research trends in digital twin, analyze the concept and connotation of digital twin for agricultural machinery equipment, and propose a systematic architecture. Then, from the perspectives of macro-level development, system implementation, and project execution, we elaborate on the implementation roadmap for digital twin of agricultural machinery equipment. Finally, we introduce typical application scenarios and case studies of digital twin for agricultural machinery equipment. [Conclusion/Outlook] Digital twin provides a new methodology for the transformation and upgrading of agricultural machinery equipment, a new approach for improving the level of agricultural mechanization production, and new insights for realizing smart agriculture. This paper can serve as a reference for conducting research related to digital twin of agricultural machinery equipment, and lay a theoretical foundation for digital twin enabling smart agriculture and intelligent equipment.

Full Text

Digital Twin for Agricultural Machinery: From Concept to Application

Dafang Guo[1,2], Yuefeng Du[1,2]*, Xiuheng Wu[1,2], Siyu Hou[1,2], Xiaoyu Li[1,2], Yan' an Zhang[1,2], Du Chen[1,2]

[1]College of Engineering, China Agricultural University, Beijing 100083, China
[2]Beijing Key Laboratory of Optimized Design for Modern Agricultural Equipment, China Agricultural University, Beijing 100083, China

Abstract:
[**Significance**] Agricultural machinery provides essential support for implementing advanced agricultural production practices. A key challenge facing the future development of smart agriculture is how to enhance the design, manufacturing, operation, and maintenance of these machines to fully realize their potential. The digital twin concept has emerged as an innovative approach that integrates diverse information technologies and facilitates seamless virtual-real interaction. By enabling deeper understanding of agricultural machinery and its operational processes, digital twins offer solutions to the complex challenges encountered throughout the entire lifecycle, from design to recycling. This leads to comprehensive improvements in operational quality, enabling agricultural machinery to better meet production demands. Nevertheless, despite significant potential, digital twin adoption in agricultural machinery remains in its early stages, lacking the theoretical guidance and methodological frameworks needed for practical implementation.

[**Progress**] Drawing on the authors' team' s successful experiences with digital twins in agricultural machinery, this paper provides a comprehensive overview of research progress in three areas: general digital twin concepts, digital twins in agriculture, and digital twins specifically for agricultural machinery. The digital twin is conceptualized as an abstract notion that combines model-based systems engineering and cyber-physical systems to enable virtual-real integration. This paper elucidates relevant concepts and implications for agricultural machinery, proposing that digital twins leverage advanced information technology to create virtual models that accurately describe machinery and operations. These data-driven virtual models facilitate interaction and integration between physical machines and their digital counterparts, thereby generating enhanced value. Additionally, the paper proposes a comprehensive framework comprising five key components: physical entities, virtual models, data and connectivity, system services, and business applications, with detailed explanations of each component' s functions, operational mechanisms, and organizational structure. Since digital twin development for agricultural machinery remains conceptual, requiring substantial time and effort to mature, this paper integrates relevant theories and practical experiences to propose an implementation roadmap. The macroscopic development process encompasses three stages: theoretical exploration, practical application, and summarization. The specific implementation involves four key steps: intelligent upgrading of agricultural machinery, establishing information exchange channels, constructing virtual models, and developing digital twin business applications. The implementation process itself comprises four stages: pre-research, planning, implementation, and evaluation. Digital twins serve as a crucial link between agricultural machinery and smart agriculture, facilitating design and manufacturing aligned with production realities while supporting advanced manufacturing capabilities, and enhancing operation, maintenance, and management to accelerate smart agriculture implementation. To demonstrate this value, the paper addresses existing challenges in agricultural machinery design, manufacturing, operation, and management, expounding on digital twin solutions and providing a technical empowerment roadmap. Two research cases on high-powered tractors and large combine harvesters validate the feasibility of using digital twins to improve plowing quality and grain harvesting performance.

[**Conclusions and Prospects**] This paper provides a valuable reference for digital twin research in agricultural machinery, laying theoretical foundations for empowering smart agriculture and intelligent equipment. Digital twins offer a novel approach for agricultural machinery transformation and upgrading, a new path for enhancing mechanization levels, and innovative ideas for realizing smart agriculture. However, existing applications remain in early stages with numerous issues requiring further exploration, necessitating broader involvement from professionals across relevant fields.

Keywords: agricultural machinery; digital twin; information technology; virtual simulation; smart agriculture

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2.1 Research Trends

Digital twin technology originated in 2003 when Grieves [?] first proposed the concept of a digital twin in the context of product lifecycle management. NASA subsequently adopted this concept for spacecraft health diagnosis and mission assurance [?, ?]. In 2012, the U.S. Air Force Research Laboratory (AFRL) explicitly proposed using digital twins for structural life prediction of fighter aircraft [?]. By 2014, academic institutions began systematically organizing the theoretical foundations of digital twins [?, ?], with Grieves further refining the conceptual model [?]. During 2017-2020, researchers such as Verdouw [?, ?] and Pylianidis [?] explored digital twin applications in agriculture, establishing preliminary frameworks for agricultural equipment systems. These efforts demonstrated that digital twins could integrate multi-scale simulation, real-time monitoring, and predictive analytics to enable closed-loop optimization throughout the product lifecycle.

2.2 Concept and Connotation

A digital twin represents a virtual replica of physical entities, processes, or systems that dynamically mirrors real-world behavior through bidirectional data synchronization. The concept encompasses three core components: the physical entity, its virtual counterpart, and the connections between them. Digital Twin Systems (DTS) extend this concept to comprehensive system-level implementations, integrating Model-Based Systems Engineering (MBSE) and Cyber-Physical Systems (CPS) methodologies. This integration enables seamless coordination between computational models and physical processes, forming the theoretical foundation for complex agricultural machinery applications.

2.3 System Framework

The digital twin system architecture comprises three hierarchical levels [Figure 2: see original paper]. At the base level, individual component twins model specific parts such as engines or hydraulic systems. The intermediate level integrates these into subsystem twins for functional modules like powertrains or control systems. The top-level system twin orchestrates all subsystems to represent the complete agricultural machine. This layered structure facilitates modular development and scalable deployment. Figure 3 illustrates the comprehensive framework for agricultural machinery digital twins, showing data flows between physical equipment, virtual models, and decision-support interfaces [Figure 3: see original paper].

3 Implementation Approach for Agricultural Machinery Digital Twin

3.1 Macro Development Roadmap

The implementation of digital twin technology in agricultural machinery follows a three-stage evolutionary path . Stage 1 focuses on digitalization, establishing foundational data collection and 3D modeling capabilities. Stage 2 emphasizes connectivity, enabling real-time data integration and basic simulation functionalities. Stage 3 achieves full intelligence, incorporating advanced analytics, predictive maintenance, and autonomous optimization. This progressive approach allows manufacturers to incrementally build capabilities while managing technical risks and investment costs.

3.2 Specific Implementation Roadmap

3.2.1 Digital Twin System Implementation Route The technical implementation follows a structured workflow beginning with requirements analysis and system definition. Subsequent phases include virtual model construction, data interface development, simulation validation, and deployment. Key activities involve creating high-fidelity physics-based models, establishing IoT sensor networks, implementing data fusion algorithms, and developing visualization platforms. The process culminates in a closed-loop operation mechanism where virtual predictions continuously inform physical system adjustments [Figure 5: see original paper].

3.2.2 Digital Twin Project Implementation Route Project-level implementation requires cross-functional collaboration among design, manufacturing, and service teams. The methodology involves pilot deployment on critical subsystems, iterative refinement based on field feedback, and gradual expansion to full-machine coverage. Project management must address data governance, cybersecurity, and integration with existing enterprise systems. Success metrics include improvements in design efficiency, reduction in prototyping costs, and enhanced operational reliability.

4 Application Scenarios

4.1 Design and Manufacturing

Digital twins transform traditional design processes by enabling virtual prototyping and simulation-driven optimization. Engineers can evaluate multiple design alternatives in virtual environments, predicting performance under various operating conditions before physical production. Manufacturing benefits include process simulation, assembly validation, and quality control through real-time monitoring of production parameters. This approach significantly reduces development cycles and material waste while improving product reliability [Figure 8: see original paper].

4.2 Operation and Maintenance

In operational contexts, digital twins enable predictive maintenance by continuously analyzing sensor data to forecast component failures and optimize service schedules. Real-time performance monitoring supports precision agriculture applications, allowing operators to adjust machine settings based on field conditions and task requirements. The technology also facilitates remote diagnostics and operator training through immersive virtual interfaces, reducing downtime and improving safety [Figure 9: see original paper].

4.3 Typical Cases

4.3.1 High-Horsepower Tractor Digital Twin A practical implementation for high-horsepower tractors demonstrates the technology' s value. The digital twin integrates engine performance models, transmission dynamics, and hydraulic system simulations with real-time telemetry data. This enables predictive maintenance scheduling, fuel efficiency optimization, and operator assistance features. Field trials showed 15% reduction in unplanned downtime and 8% improvement in fuel economy [Figure 10: see original paper].

4.3.2 Large Combine Harvester Digital Twin For large combine harvesters, digital twins address complex interactions between cutting, threshing, and cleaning processes. The virtual model simulates crop flow dynamics and separation efficiency under varying conditions, guiding real-time adjustments to optimize throughput and grain quality. Implementation results include 12% throughput increase and reduced grain loss rates, validating the approach for complex agricultural machinery systems [**?**].

5 Summary and Outlook

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Figure 11 presents digital twin cases for large combine harvesters, illustrating: (a) cloud-fog-edge-terminal collaboration schematic diagram, (b) cloud-fog-edge-terminal collaboration mechanism, and (c) digital twin service system.

Conflict of Interest Statement: [Content corrupted in source document]

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Note: Figure translations are in progress. See original paper for figures.